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Résumé

On a mis au point une méthode servant à fabriquer un échantillon en forme d'os pour chiens ou d'haltère dont la section de mesure uniforme, faite de n'importe quelle glace naturelle, permet d'effectuer sur celle-ci des contrôles en traction. Les bouts de l'échantillon sont faits de glace multicouche et la géométrie de la coupe transversale est compatible avec la structure granulaire de la glace. La section de mesure est assez grande, de sorte qu'elle peut contenir un nombre de grains suffisant pour éviter tout effet géométrique et qu'on peut y monter la jauge de déplacement pour effectuer des essais à des vitesses de déformation constantes à l'aide d'un appareil fonctionnant en boucle fermée. L'utilisation de la technique est illustrée par des exemples de résultats d'essais auxquels a été soumise de la glace de mer à grains prismatiques, sous forme de carottes de 300 mm de diamètre, provenant d'un floe pluriannuel de l'Extrême Arctique. L'auteur décrit aussi des méthodes servant à effectuer des analyses microstructurales après essais.

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CLOSED-LOOP CONTROLLED TENSILE STRENGTH TESTING METHOD FOR MULTI-YEAR SEA ICE

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Abstract

A method has been developed for making a dogbone- or dumbell-shaped specimen with a uniform gauge section made of any natural ice to be tested in tension. The specimen ends are made of built-up ice and the cross-sectional geometry is compatible with the grain structure of the ice. The gauge section is large enough to contain a sufficient number of grains to avoid any geometric effect and to mount the displacement gauge for conducting tests under closed-loop controlled constant strain rates. The application of the technique is illustrated by examples of test results on columnar-grained sea ice obtained from a multi-year floe in the High Arctic in the form of 300 mm diameter cores. The paper also describes methods of carrying out post-test microstructural analysis.

Introduction

Tensile tests in polycrystalline metals, alloys and ceramics are normally performed using dumbell- or dogbone-shaped specimens. This type of geometry helps in generating the maximum stress and strain field in the gauge section and at the same time maintains the deformation field uniform in this zone. The size of the specimens to be used is usually dictated by the test facilities available and the machinability of the material. Since the grain sizes are small, it is often assumed, and rightly so, that there are a large number of grains across the diameter or the minimum dimension of the gauge section.

The grain size of natural polycrystalline ice is usually several orders of magnitude larger than that of metals, alloys and ceramics. The specimen size for ice should therefore be huge compared to that for other materials if a sufficient number of grains (more than ten grains, according to Jones and Chew, 1981) is to be accommodated within the specimen to avoid any geometric effect. Providing an adequate specimen size for direct tensile tests on fine-grained, granular ice is not difficult (Hawkes and Mellor, 1972; Burdick, 1975) but it has been a chronic problem in testing natural ice (Peyton, 1966, Saeki et al, 1978). This is because of the difficulty of transporting large amounts of ice from the field to the laboratory. However, many tests on laboratory grown saline ice have also been carried out in which this constraint was overlooked or ignored. Thin-section photographs of fractured specimens show only two grains (Fig. 30 in Dykins, 1970) and three grains (Fig.15 in Dykins, 1967 and Fig. 6 in Dykins, 1969) across the specimen diameter. All these authors used specimens with reduced-section diameter or width in the range of 30 mm. Moreover, no direct measurements of strain in the gauge section were carried out. An improved method for tensile testing of ice and frozen soil, using special end caps and a pair of displacement gauges mounted on the gauge section, was presented by Eckardt (1982). This procedure was essentially followed by Kuehn et al (1988) who used Synthane end-caps described by Lee (1986).

The most significant aspect of the new test technique is the fact that it uses the same specimen geometry as the test specimens used for metals, alloys and other materials. However, the final finished ice specimens are very large (overall length up to 700 mm has been used), significantly different from typical tensile test specimens generally required for other materials.

This technique, originally developed for fresh-water ice, has been adopted for testing first-year as well as multi-year sea ice. Special treatments of the specimen are required for such types of ice. It has been successfully applied in tensile testing of columnar-grained ice from a multi-year floe in the Canadian High Arctic under closed-loop controlled constant strain rates. This paper will describe the technique and give some results to show its general applicability.

Description of Available Field Ice

It is common practice to obtain ice from the field in the form of blocks or cylindrical cores. Ice testing depends greatly on the availability of ice cores or blocks large enough to make the required specimen. Blocks are suitable for obtaining samples from the top layers of natural ice masses. Since chain saws are used, it is extremely difficult to reach depths greater than one metre. Accordingly the core method is more commonly employed. However, the core augers readily available have diameters in the range of 76 mm to 100 mm and can, therefore, only provide enough material for specimens that are vertically oriented with respect to the ice cover. This, in fact, limited Kuehn et al (1988) to test only vertical samples of natural sea ice with reduced gauge-section diameters less than 80 mm. For most engineering situations with floating ice covers the stress is applied in the horizontal plane parallel to the plane of the ice cover and horizontally oriented specimens are required for testing.

Sea ice has been commonly seen to be columnar-grained exhibiting either transverse isotropy or orthotropy in its crystallographic structure. For this type of ice and for loads applied in the horizontal plane or the plane parallel to surface of the ice cover (normal to the longitudinal axis of the grains) prismatic, rather than cylindrical, specimens are compatible with the grain structure (Figure 1). This is because a cylindrical specimen has non-uniform grain constraint for columnar-grained ice because the grains are of different lengths within the specimen and grain-boundary sliding mechanism plays an important role in the deformation and fracture

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processes. Moreover, a significant amount of valuable material (in case of field samples) is wasted in making cylindrical specimens. These considerations led the author to use prismatic specimens for creep (Sinha, 1978) as well as for strength tests on fresh-water ice (Sinha, 1981) and sea ice (Sinha, 1984). The compressive strength of first-year sea ice and its rate dependence presented in Sinha (1984) and obtained on small samples (0.1 m x 0.05 m x 0.25 mm) was shown to be in excellent agreement with the results obtained on 3 m x 1.5 m x 6 m specimens by Chen and Lee (1986). The compatibility questions, however, were not given any consideration in most tensile tests.

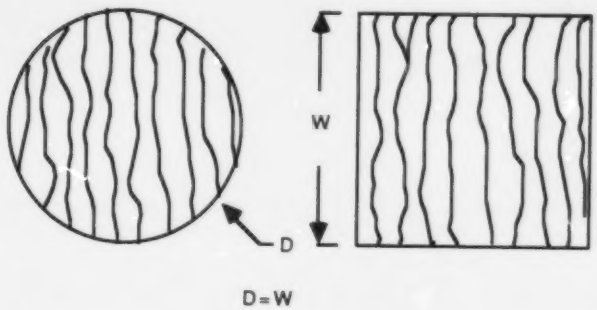

Figure 1. Cross section of a cylindrical (a), and prismatic (b), specimen of columnar-grained ice, each containing ten grains across the sample

Special core augers have been made and used successfully to obtain cores with large diameters. An example can be seen in Sinha et al. (1986) in which vertically oriented cores with a diameter of 300 mm were obtained from a floating drilling platform in the High Arctic. These cores were sectioned into 120 mm thick discs from which rectangular specimens, with dimensions of 100 mm x 100 mm x 250 mm, could be made for compression tests with loads applied in the horizontal plane, that is, parallel to the plane of the ice platform. However, horizontally oriented tensile specimens with a sufficiently large gauge section could not be made using these cores. This dilemma prompted the development of the following technique.

Specimen Preparation

Figure 2 shows possible geometries of dog bone-type tensile specimens that can be fabricated using small samples of ice obtained from blocks or large-diameter cores. The diagram shown is for making a specimen with a rectangular cross-section. This geometry, as discussed earlier, is compatible with commonly available columnar-grained ice. In order to increase the surface area for bonding between the test ice and the built-up ice, the ends of the test sample are cut to resemble a saw-tooth -an operation performed easily with a band saw. A complete specimen, before the holes are made in the end sections, is shown in Figure 3. This specimen was made from a transparent test section to show clearly all the features of a final specimen including the saw-toothed boundaries between the ice to be tested and the built-up ice.

Specimens are prepared inside a cold room at - 10°C for freshwater and old sea ice with low salinity, as in the present case (room temperature should be lowered to about - 22°C for young and first year sea ice with high salinity). The rough sawtooth cuts at the ends are sealed completely with a layer of pure ice about 2 mm in thickness. This thick layer is built up by successively spraying fine mists of distilled water at a temperature slightly above 0°C. The layer protects the structure and the texture of the specimen from the subsequent fabricating process because natural ice contains impurities such as air or gas bubbles and brine pockets. The main surfaces of the specimen are then covered with a layer of paper soaked in chilled water. This frozen layer of paper serves as a marker during the final machineing stage.

After the sealing operation is completed, the block of ice is placed in the centre of a specially designed box as shown in Figure

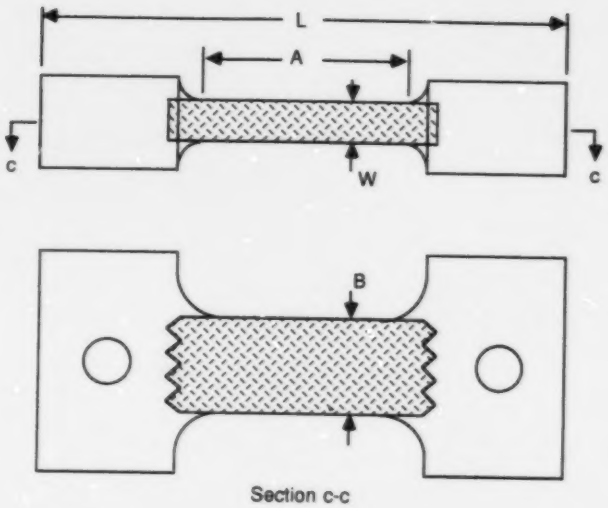

Figure 2. Pin -loaded tension specimen. B,W,A > 10d (grain size)

Figure 3. A specimen (without holes) with gauge section made of transparent freshwater ice

4. End sections are then built up by successively adding layers of ice, about 10 mm in thickness, using an ice-water slurry made of distilled and de-aerated water and fine-grained ice seeds that passed through a standard sieve with a mesh size of 1 mm. This process is adopted to protect the test section from pressures that could develop during freezing and could induce microcracks. To minimize the machineing time and to avoid unwanted warming effects that could induce brine drainage, spacers are used in the box as shown. To prevent adhesion to the box, the walls of the box and the surfaces of the spacers are lined with a layer of thick polyethylene. When the freezing process is complete, the ice block can be removed easily by unscrewing the two side panels of the box.

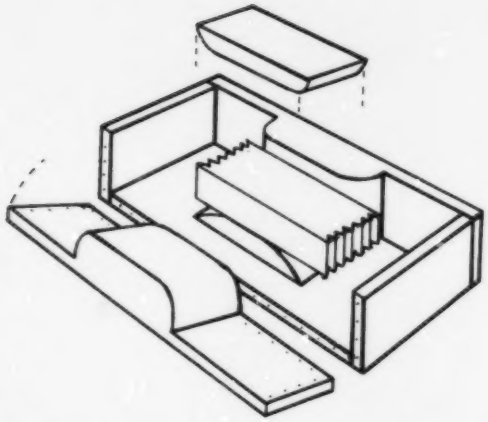

Figure 4 Special box for fabricating the specimen

The final dog bone-shaped specimen is then prepared using a milling machine inside the same cold room used for the fabrication process. Care is taken to remove completely the layer of paper and ice used for sealing. A drilling machine, in conjunction with a jig to hold the specimen, is then used for making holes in the two end sections of the specimen and on the longitudinal axis of the specimen. Any cutter marks on the inside surface of one of the end holes are removed by inserting the pin, at a temperature of slightly above 0°C, and allowing the specimen to hang and swing freely, in a vertical position from the pin holder attached to the upper universal joint in the test machine, until the pins are cold and the melted thin layer of ice are frozen. This operation is repeated for the other end of the specimen. These procedures are followed to insure good fit and rotational movement of the specimen around the loading pins. Cutter marks on the surfaces in the gauge section of a specimen are then removed carefully with fine sandpaper followed by a polish with tissue paper slightly moistened (not soaked) with alcohol. Although the milling operation can be performed with an accuracy of 0.02 mm, the ends of the specimens are symmetrical in width with the centre line of the reduced section within about 0.5 mm (see ASTM,1987).

Test Procedure

A commercial closed-loop, servohydraulic system (MTS) of 1.0 MN capacity situated inside a cold room near an observation window is used. The cold room is maintained at a temperature of $-10°C \pm 0.1°C$ and the controls, pump, and all of the recording system are kept outside in a warm room.

The loading train consists of two commercially available universal tension joints and two specially designed tensile pin holder-universal joint systems (one at the top and one at the bottom of the specimen, Figure 5) and a 250-kN capacity load cell. The specimen holders are designed to allow a small confining pressure (if required) through a set of parallel plates, covered with thick layers of polyethylene sheets, and screws (Figure 6). The lower holder is attached to the actuator and the upper holder is suspended from the cross-head via the load cell. The machine can be programmed to apply various amounts and rates of load, strain, and displacement. Axial strain rate, $\dot{\varepsilon}$, is maintained constant by a feedback system employing a 150 mm (or 200 mm) gauge-length extensometer attached directly to the central area of one face in the gauge section (Figure 6). The extensometer is mounted on the specimen using two specially designed metal holders (details given in Sinha, 1986) frozen to the top and the bottom of the gauge section of the specimen. Load and strain outputs are recorded separately, as functions of time, on strip chart recorders and on a digital data logging system outside the cold room.

After completion of a test, two thin sections are made from the tested ice - to examine the vertical as well as the horizontal profile of the grain structure. Thin sections, about 0.5 mm in thickness, are prepared by the double microtome technique developed specifically for sea ice and described in detail in Sinha (1977). The main advantage of this method lies in the clarity with which the

Figure 5 One of the two universal tensile joint and pin holder systems used in the load train

(a) (b)

Figure 6 A multi-year sea ice specimen before test (a) and after test (b)

microstructure of sea ice can be examined; conventional methods, commonly practised in ice laboratories, disturb the microstructure and often add artifacts.

About a third of the gauge section of the specimen is melted after testing to determine the salinity of the ice. These measurements, along with the salinity measurements obtained before the tests, allow one to check whether the salt content of the ice has changed as a consequence of the fabrication and testing procedure. It should be mentioned here that the large core provides plenty of ice, in addition to the specimens, to carry out pre-test salinity profile and microstructural studies similar to the description given in Bjerkelund et al (1985).

Figure 9a shows a mid-plane thin section of the specimen in Figure 6. This thin section was prepared by the double-microtoming technique developed earlier to avoid the artifacts that are introduced by the usual thin sectioning method (Sinha, 1977). The photograph of the section under cross-polarized light shows that the ice had a preferred orientation with the c-axis of the sub grains tended to be parallel to the long axis of the specimen and hence the direction of the load application. The built-up ice filling the saw-toothed section of the original rough cut can be seen at the lower end of the photograph. Note the granular ice with small grain sizes, less than 1 mm, in the added end section.

The location of the fracture surface is revealed in the

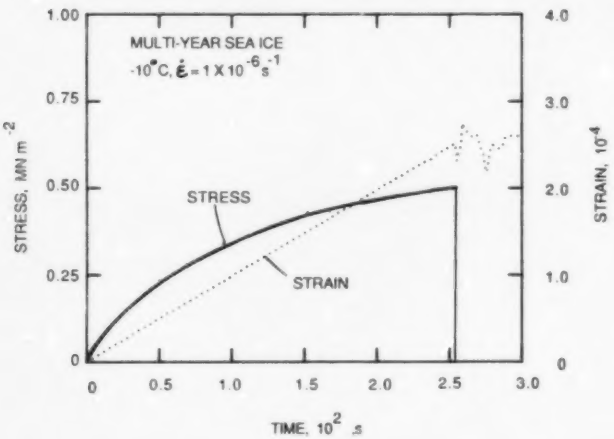

Figure 7 Stress and strain history for a tensile test on multi-year sea ice at a strain rate of 1 x 10^{-6} s^{-1}

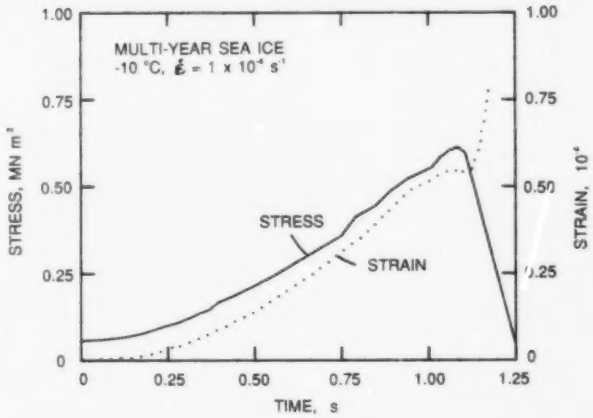

Figure 8 Stress and strain history for a tensile test on multi-year sea ice at a strain rate of 1 x 10^{-4} s^{-1} corresponding to the specimen in Figure 6

Results

Using the techniques described above, tests have been conducted successfully in a wide range of strain rates An example of a test result of multi-year ice at a strain rate of 1 x 10^{-6} s^{-1} is shown in Figure 7. The linearity in the strain history shows that the test system responded well. The stress history, however, indicated that the ice responded in a rather nonlinear manner.

Figure 8 shows test result at a strain rate of 1 x 10^{-4} s^{-1}. It can be seen that the test system reacted rather slowly and took about 0.5 seconds before it could impose the specified strain rate. Such a lack of control in the test system can not be revealed by the customary stress-strain diagram as has been pointed out earlier (Sinha, 1981). This was one of the worst cases recorded during the tensile tests. This example is reproduced here to show the limitations of even a well-tuned closed-looped system. It was shown earlier during compression tests, where the load train was relatively simple, that the system could operate well up to a strain rate of 2 x 10-3 s-1 (Sinha,1986) and that the system required about 40 milliseconds to respond (Sinha, 1988). The slow response in the present case of tensile tests could be due to the added softness and the complexities of the load train used. More studies are required to confirm this point.

The state of the specimen before and after the test, corresponding to the test in Figure 8, are shown in Figure 6. It may be seen that the fracture occurred in the gauge section. A single crack, formed in the lower half of the specimen, caused failure. In this case the specimen was oriented in the horizontal plane and the gauge section had a dimension of 50 mm x 100 mm x 150 mm with the 100 mm x 150 mm face parallel to the plane of the ice cover and normal to the length of the columnar grains.

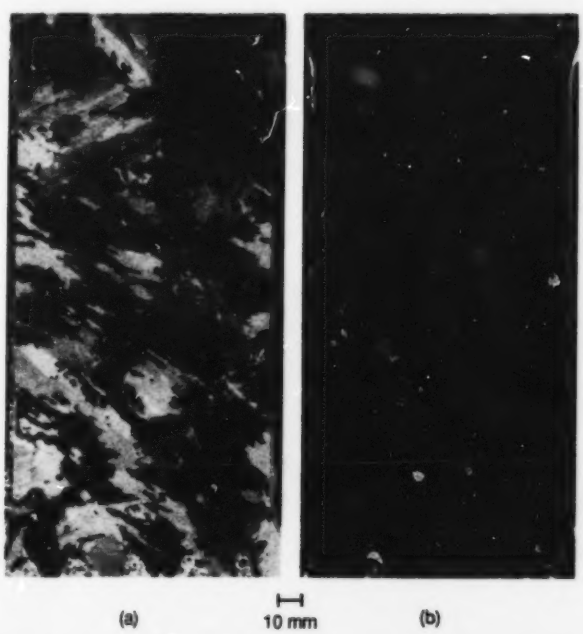

Figure 9 Mid-plane thin section of the specimen in Figure 6 after test observed under cross-polarized light (a) and under scattered light (b).

macrograph (Figure 9b) taken under scattered light (Sinha, 1977). The entrapped impurities and the voids in the ice including a brine channel are made visible by this method. Note that the crack passes through a large circular void on the left of the specimen. Figure 10 shows a photograph taken using a combined scattered-light and polarized-light technique (Sinha,1981). Many details of the structure and the texture of the ice are made visible. It can be seen that the small changes in the orientation of the crack was influenced by the microstructure. On the left hand side near its probable origin at the circular voids, the crack propagated parallel to the sub-grain boundaries. The figure also shows that the crack became trans-sub-granular as it progressed to the right hand side. This transcrystalline characteristics of the crack propagation can be seen clearly in the micrograph shown in Figure 11. In this micrograph the sub-grain boundaries are revealed by thermal etching following microtoming (Sinha, 1986). It should be mentioned here that the microstructural details described above can not be revealed by the conventional thin sectioning and photographing methods. In all the photographs illustrated by Dykins (1967, 1969, 1970), for examples, the fracture planes in columnar-grained saline ice were shown as bands, up to 5 mm wide, of fine-grained granular ice.

Summary

A new method has been developed to fabricate dumbell- or dogbone-type specimens with ends made of built-up ice and gauge sections made of ice to be tested in tension. Using this technique it is possible to test many types of natural ice if the available ice block for testing is larger than the size necessary for the required gauge sections. The gauge sections are made to be large enough to contain a sufficient number (greater than ten) of grains across their width, to avoid any geometric effect, and long enough to install a large displacement gauge (longer than ten grain diameters) directly on the ice in the gauge section. The specimen geometry is suitable for tensile testing under closed-loop controlled constant strain rate loading conditions with the controlling displacement gauge mounted directly on the specimen. Specimens with cylindrical gauge sections can be made for isotropic, granular ice with equiaxed grains. For columnar-grained ice, however, prismatic gauge sections with rectangular cross-sections are more compatible with the geometry of the grains than are circular cross-section.

Figure 10 Mid-plane thin section of the specimen in Figure 6 after test photographed using a combined scattered-light and polarized-light technique.

Figure 11 Details of the crack near the center of the thin section in Figure 10. Sub-grain boundaries are revealed by etching.

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